Economically sustainable growth of perovskite photovoltaics manufacturing

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Abstract — **The significant capital expense of photovoltaics (PV) manufacturing has made it difficult for new cell and module technologies to enter the solar power market and compete on price with incumbents. We present a technoeconomic model that evaluates the sustainable growth rate of perovskite manufacturing companies, focusing on the dual impacts of economies of scale and average selling price on profitability. A cost model for a roll-to-roll perovskite PV manufacturing facility versus scale is presented and used to establish minimum sustainable prices from $3.3/W – $0.53/W for flexible modules manufactured in factory sizes ranging from 0.3 MW/year to 1 GW/year respectively. We use these numbers to calculate the economically sustainable annual growth rates for a company selling photovoltaic modules in different markets, obtaining a wide range of possible values, depending on operating margin and scale of manufacturing. Selling into the mainstream utility market for $0.4/W requires a prohibitively large upfront investment of over $1 billion to establish a profitable manufacturing facility. We show that the required investment, and thus the barrier to market entry for flexible perovskites, can be reduced in two ways: (i) lowering the cost of materials to 70% of current values reduces the initial investment required to <$100 million, highlighting the role of disruptive innovations in related industries, or (ii) selling into niche markets for $1/W or greater, representative of IoT, BIPV, and vehicle-integrated markets, reducing the required initial capital investment to <$10 million. In addition, we show that it is possible to sustainably grow a perovskite manufacturing company, considering US labor rates, by selling products in growing alternative PV markets.**

I. Introduction

To mitigate the impacts of climate change, terawatts of solar power must be deployed over the next decade [1]. We have previously shown that this cannot be achieved in a financially sustainable manner using current technology alone, as the capex for silicon photovoltaics (PV) manufacturing remains too high and the efficiency of the technology remains too low to drive the required demand [2]. It is thus desirable for higher-efficiency and lower-cost photovoltaic technologies to be successfully commercialized over the coming years. However, new cleantech technologies have historically struggled to scale up [3], [4], with their capital intensity resulting in long timelines for commercialization that are incompatible with traditional venture capital funding models [5], that lead to lower success rates for cleantech startups compared to software and medical ventures [6]. In this paper, we use bottom-up cost modeling to explore economically sustainable strategies for one new cleantech innovation, solution-processed perovskite photovoltaics, to scale up and enter the mature solar power market. Our goal is to help illuminate one or more pathways that could enable this groundbreaking technology to successfully scale-up and navigate the journey from lab bench to market [7]–[9].

The path to market success is not clear — today's leading PV module manufacturers drive down prices by producing modules at the GW/year scale, largely in regions with low labor costs. As a result, it is difficult for new entrants to compete with established

PV manufacturers on price. Thus many seek to commercialize their products in growing alternative markets such as the Internet of Things (IoT) applications, building-integrated photovoltaics (BIPV), telecommunications, vehicle-integrated, and others where higher margins are possible [10]–[12]. Here we show that such strategies can enable a sustainable route to scale, allowing perovskite manufacturing companies to leverage higher prices in alternative PV markets to overcome the capital intensity barrier for new cleantech products, and reach significant scale before entering the wider solar power market [1]. Before proceeding, it is worth noting the growth of First Solar Inc., where a number of years after its initial founding, the company scaled its manufacturing capacity from 6.5 MW/year to over 1 GW/year over 5 years at a compound annual growth rate of 180% [13], [14]. As outlined in Fig. 1 (a) & (b), this led to module manufacturing costs dropping from \$2.94/W to \$0.83/W, *i.e.* 22% per year, over the same period — highlighting the rapid growth and cost reduction that can be achieved under the right circumstances.

In the rest of this paper we model how the module manufacturing cost for a perovskite startup decreases with increasing scale and the subsequent sustainable growth rates that can be achieved. We begin in Section II by developing a bottom up technoeconomic model of solution-processed flexible perovskite photovoltaic modules and calculate the minimum sustainable price versus manufacturing scale. In Section III, we use this cost model to analyze the potential growth rates for perovskite photovoltaic module manufacturing companies as a function of their size and the average price they obtain for their products, to understand how perovskites can gain traction and significant market share. We continue by estimating the capital investment levels required to establish profitable companies of different scales in various markets.

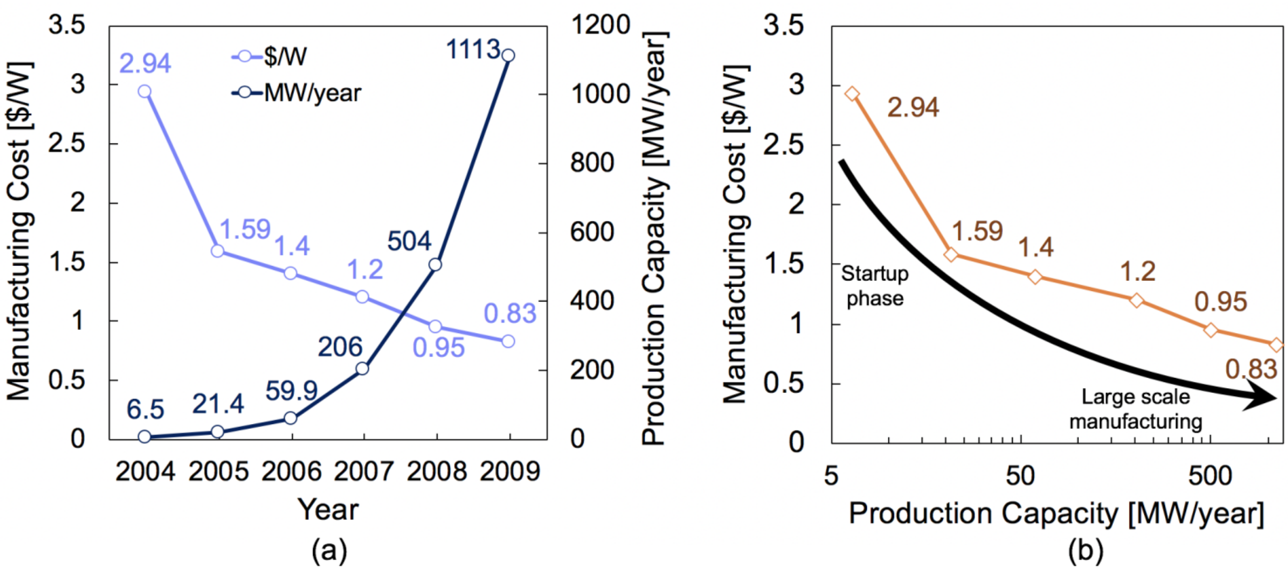

Figure 1: (a) The manufacturing cost and production capacity of First Solar during the early stages of the company's development from 2004 – 2009, and (b) the manufacturing cost versus production capacity showing the influence of economies of scale.

II. The limiting role of capex in growing photovoltaic companies

The capital expenditure for module manufacturing equipment (capex) plays a significant role in the minimum sustainable price (MSP) of many existing PV technologies [15]. To illustrate this point, in this section we provide the minimum sustainable price of photovoltaic technologies as a function of the capex required for the absorber layer only, *i.e.*, the cost of the bulk material deposition tools considering solution processing, chemical and physical vapor deposition, and epitaxial technologies [16]. This analysis is conducted considering a large-scale manufacturing facility of 100 MW/year and we present the results in $/m^2 (as opposed to $/(W·year)), representing the portion of capex paid for on a per module area basis, for ease of comparison between technologies with different power conversion efficiencies. To examine the limitations of these different deposition techniques, average selling prices (ASP) for the final products are assumed and the operating margin and sustainable growth rate are calculated to illustrate capex's growth-limiting effect.

Figure 2 (a) outlines the module MSP for different photovoltaic material systems as a function of absorber deposition capex assuming material costs of $30/m^2 and a factory size of 100 MW/year. On the high end of the capex scale are epitaxial technologies such as those used to manufacture III-V solar cells – the higher cost of deposition tools and slower throughput for these thin-film manufacturing techniques lead to capex making up a significant portion of the final module cost that is difficult to minimize by moving to large scale manufacturing [17]. It has recently been shown that dual-junction GaInP/GaAs solar cells with an efficiency of 30% have a manufacturing cost of $21/W for a 50 MW/year production capacity if five substrate re-uses are achieved [18]. Physical and chemical vapor deposition of CdTe and CIGS exhibit lower capex contributions to the final module cost and has enabled these technologies to become established photovoltaic technologies [19]. Our recent bottom-up cost modeling of single-junction CdTe and CIGS modules showed their absorber depreciation values were $6.4/m^2 and $10.3/m^2 with module MSPs of $0.3/W and $0.36/W, respectively [19]. While these MSPs are low, the capex contribution limits the potential growth of manufacturing capacity, as larger profits must be obtained to cover the expense of building new manufacturing facilities. Solution-processed photovoltaics have the most potential to minimize the impact of capex on module cost owing to the use of relatively facile printing or roll-to-roll manufacturing and the rapid throughput possible. Solar modules that can be solution processed using organic, dye-sensitized, perovskite, or quantum dot materials could greatly reduce the selling price required to make a company sustainable.

By assuming absorber deposition dominates total capex – Figure 2 (b) moves beyond the minimum sustainable price and shows the impact of capex on the sustainable growth rate of photovoltaic manufacturing companies versus the average selling prices for their products. The average selling prices we consider range from those obtainable in the mass solar power market, $0.3/W – $0.5/W, all the way up to $3/W, *i.e.*, prices that can be reached in the IoT, BIPV, and telecommunications markets. Based on our assumptions of 100 MW/year annual production capacity and $30/m^2 material costs, the results outline a number of important points:

- To grow sustainably, a company selling modules for $0.3/W needs to manufacture with absorber deposition capex of less than $10/m^2, *i.e.*, solution processing or high-rate vapor deposition.
- Selling modules for $0.5/W or less requires a company to operate with a capex of $40/m^2 or less to maintain sustainability.
- From this simplified analysis we see that products produced using solution processing, with a capex contribution to module cost of $0.1-1/m^2 at 100 MW/year scale, can achieve sustainability in all photovoltaic markets. The calculated sustainable growth rate increases by almost an order of magnitude from ~70%/year to ~650%/year as the selling price increases by an order of magnitude. This is not true for other deposition techniques, *i.e.*, solution processing squeezes out capex's influence on company sustainability.

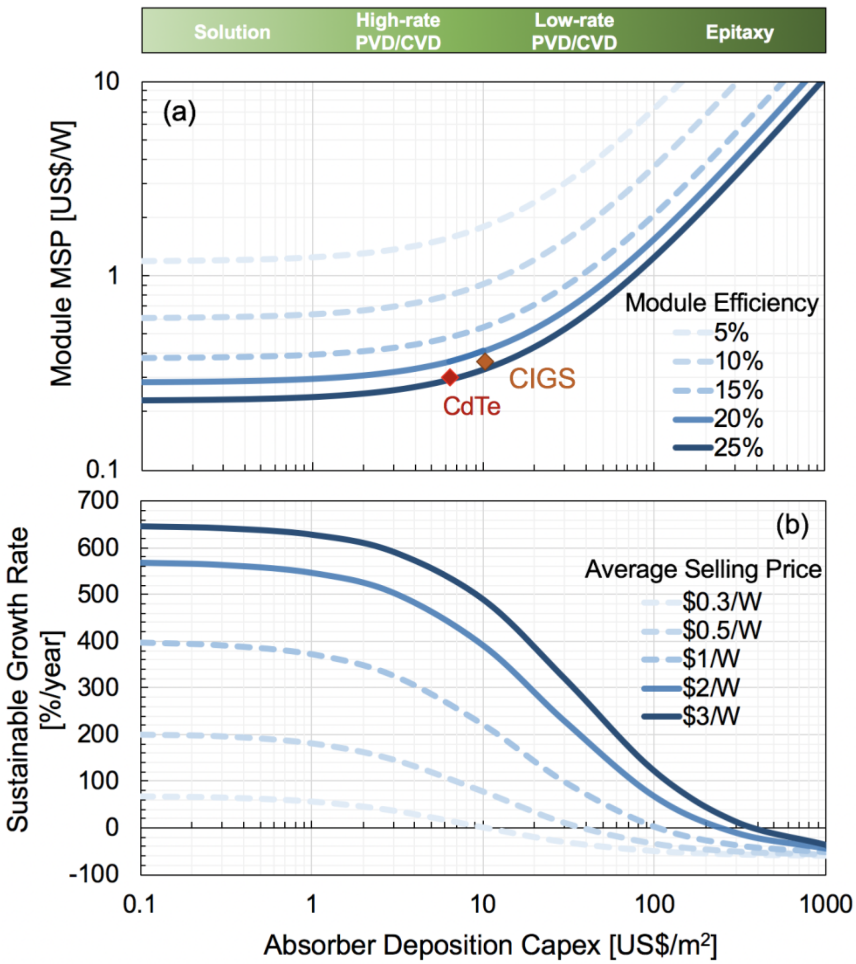

Figure 2: (a) Sensitivity of module MSP to absorber deposition capex with modeled values for CdTe and CIGS in [19] highlighted and, (b) the sustainable growth rate of photovoltaic manufacturing versus absorber deposition capex and average selling price.

III. Perovskite manufacturing costs versus scale

While recent techno-economic analyses established minimum sustainable prices for perovskite photovoltaic modules on glass of \$0.3/W — \$0.7/W, these studies limited their analysis to larger factory sizes of 100 MW and greater [20], [21]. To address the question of the cost of small-scale manufacturing, we develop a cost model for a perovskite PV module factory versus scale, building on work by Chang *et al.* [22], and assess the module manufacturing costs considering economies of scale. We evaluate the cost of producing perovskite modules in the U.S. using a single roll-to-roll printing line with a maximum production capacity of 3.6 MW/year, up to 1 GW/year and 278 printing lines, considering the realistic impact of scale on costs including material prices versus purchase volume, US labor costs, and facility costs. In this study we focus on the manufacture of flexible single-junction modules as opposed to modules on glass or perovskite-on-silicon [23], [24] or perovskite-perovskite tandems [25], [26] given the lower expected influence of capex in solution processing as described in the Supplementary Information.

We develop a bottom-up cost model for a roll-to-roll solution processing perovskite photovoltaic module manufacturing facility, which is summarized here and outlined in detail in the Methods section. The manufacturing cost model includes the materials consumed and tool depreciation following a step-by-step process required to produce the module structure outlined in Fig. 3 (a). The seven steps involved comprise: the purchase of indium-tin-oxide coated polyethylene terephthalate (PET-ITO), laser pattering of the ITO layer, slot-die coating of (i) the perovskite absorber, (ii) ZnO nanoparticles, and (iii) the hole-conducting PEDOT:PSS layer, screen-printing of a Ag back contact, encapsulation in barrier foils using a laminator, cutting and contacting, and a final module testing step. Additional costs considered include the cost to purchase the buildings and facilities, labor for tool operations, tool maintenance including capital and labor expenses, facility and tool electricity usage, R&D expenses and selling, and general and administrative expenses (SG&A). Specific values are provided in the Methods Section.

To model the impact of increasing production scale, for all materials used, quotes for material costs versus purchasing volume were obtained. The purchase volumes used were the amount (kg, L, or m^2) of materials required for 3 months of manufacturing, *i.e.*, it was assumed materials adequate for 3 months of manufacturing were purchased at once and stored on site before use. The economies of scale for purchasing the manufacturing tools of a 10% reduction in price for every doubling of purchase volume was assumed [27]. Our model considers manufacturing lines that are in use 24 hours a day for 365 days per year and the minimum annual production for one printing tool is 3.6 MW/year. When modeling annual productions of less than this value, we use the capex value to purchase one printing line and the required facility size. Other costs we adjust for scale include the portion of revenues spent on R&D which we assume reduce from 20% for small scale manufacturing of 1 MW/year to 10% once a scale of 1 GW/year is reached. The SG&A is assumed to be reduce from 12% to 8% across the same range – we note the current percentage of revenues spent on R&D by today's top 12 PV companies is ~2%, and SG&A is ~11% [28]. The factory is assumed to suffer from 5% downtime for maintenance and repairs, while a final module efficiency of 18% and a PV industry standard weighted average cost of capital (WACC) of 14% was used to calculate the cost and MSP in $/W across all scales.

As summarized in Fig. 3 (b), the modeled MSP for perovskite solar panels manufactured on plastic film range from $3.3/W for a small-scale annual production of 0.3 MW/year to $0.53/W for an annual production capacity of 1 GW/year. At small scales of less than 3 MW/year, when one printing tool is purchased but underutilized, there is a relatively even distribution of cost contributions from capex, materials (variable), R&D, and SG&A. As the scale of production increases to 10 MW/year, the cost of manufacturing decreases to $0.8/W and less, with material costs contributing most. The results show that for solution processed photovoltaics, a relatively low manufacturing cost can be achieved at relatively small scales owing to the low capex contribution of R2R tools to the final module cost.

Given that at all scales, the variable or material costs make up the largest portion of the final module costs, it is worth considering these in more detail. Fig. 3 (c) & (d) show the step-by-step cost contributions from two ends of the manufacturing scale, 3 MW/year (1 printing line is utilized 80% of the year) and 1 GW/year. In both cases, a significant contribution to cost is the purchase of the three plastic foils used in the module manufacturing including the initial PET-ITO substrate and 2 layers of encapsulating barrier foil.

It should be noted than $0.53/W is not low enough to sell into the residential or utility scale photovoltaic markets at a profit given recent module prices have been in a $0.2/W — $ 0.4/W range [29], however, given our model is limited to one cell type and its associated cost of materials, we expect some advances in technology will reduce the projected costs for R2R perovskites before they reach GW-scale production. Our model outlines that research into these 'advances' should focus on driving down the cost of materials including TCO-coated substrates, metal contact deposition, and barrier foils in combination with intrinsic perovskite materials stability. This section makes clear the importance of a combined optimization of the technical, manufacturing, and economic aspects of perovskite photovoltaics to enable scale-up.

Given the number of assumptions involved in an analysis like this, we conduct a sensitivity analysis on MSP for some key assumptions and costs and present the results in Figs. 3 (e) & (f). Fig. 3 (e) presents results from a sensitivity analysis for a 3 MW/year annual production and Fig. 3 (f) presents the results from a sensitivity analysis for a 1 GW/year annual production considering a 30% decrease or increase in module efficiency, labor cost, materials purchasing frequency, prices for all materials, prices for barrier foils only, prices for PET-ITO films only and the costs to purchase all required tools. It is clear that, given the higher portion of the manufacturing costs attributed to variable costs as compared to capex depreciation, changes in the price of materials have a greater impact on module MSP than increases in tool costs. A 30% decrease in module efficiency also increases MSP significantly given that 30% less Watts are now produced per unit cost, re-emphasizing the importance of increasing the efficiency of currently demonstrated perovskite solar cells manufactured by high-throughput methods. In terms of reducing the MSP of this technology, it is clear that any technology that can reduce the cost of materials can have a significant impact with a 30% reduction in the cost of all materials reducing the MSP from $1.02/W to $0.83/W for the 3 MW/year production capacity and $0.534/W to $0.44/W for the 1 GW/year production capacity.

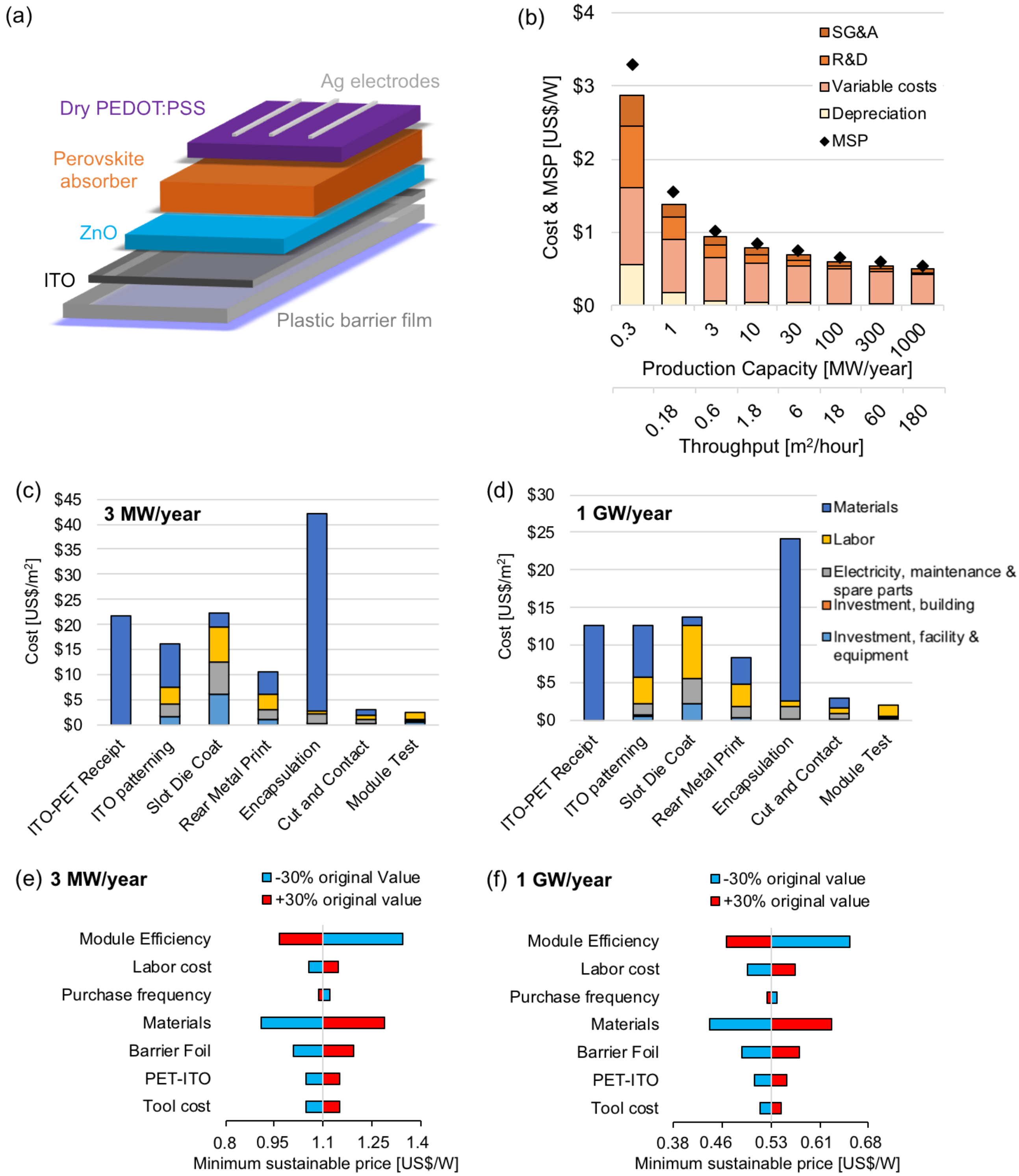

Figure 3: (a) Outline of the cell structure modelled, (b) the production cost and MSP for R2R perovskite modules versus scale, (c) breakdown of the costs per manufacturing step at 3 MW/year production capacity, (d) breakdown of the costs per manufacturing step at 1 GW/year production capacity, (e) sensitivity of the module MSP to various parameters at 3 MW/year production capacity, and (f) sensitivity of the module MSP to various parameters at 1 GW/year production capacity.

IV. Sustainable growth of perovskite manufacturing

Having established a range of costs for perovskite manufacturing versus scale, in this section we calculate the sustainable growth rate of a perovskite PV company versus its scale and the ASP of its products. The growth rate calculation follows the method in [2] where the portion of operating profits not used to pay for R&D and SG&A is assumed to be spent on purchasing new capex equipment and facilities to expand manufacturing capacity. For this analysis, average selling prices for photovoltaic products that range from 0.3 – 10 $/W were considered, representing the possible values across a wide range of PV markets from utility-scale systems to unmanned aerial vehicles [10]. Fig. 4 outlines the sustainable growth rate of a perovskite manufacturing facility versus its scale and the average price products are sold for, assuming growth would not be constrained by demand. For production capacities of under 1 MW/year where manufacturing costs are typically > 1 $/W, larger average selling prices are required for profitability and growth – it should be noted, however, that these prices are available for products that can be adapted to niche PV markets for drones and IoT nodes. For the R2R process we have modeled, the minimum sustainable price drops below 1 $/W as the factory scales up, reaching a minimum of 0.53 $/W at a scale of 1 GW/year. The growth rates for medium sized companies of 10 – 100 MW/year are positive for average selling prices of >1 $/W. Growth rates of 100% and greater are readily achievable for average selling prices obtainable in alternative PV markets and show that perovskite manufacturing can be compatible with venture capital funds who typically look for growth opportunities with return on investments equivalent to ~100% year-on-year growth. We use growth in production capacity as a comparison for different R2R perovskite manufacturing facilities and highlight this 100% growth benchmark as a dashed line in Fig. 4. We see that for perovskite manufacturers to reach >100% growth requires significantly different levels of ASP, as a function of production capacity. A small-scale (1–10 MW/year) factory must secure a minimum 1.5–3 $/W ASP for their products, while larger factories must sell for at least 1 $/W and the largest modeled (1 GW/year) must sell for 0.72 $/W. This value is around double the typical price currently obtained for photovoltaic modules in the grid-connected residential, commercial, and utility PV markets.

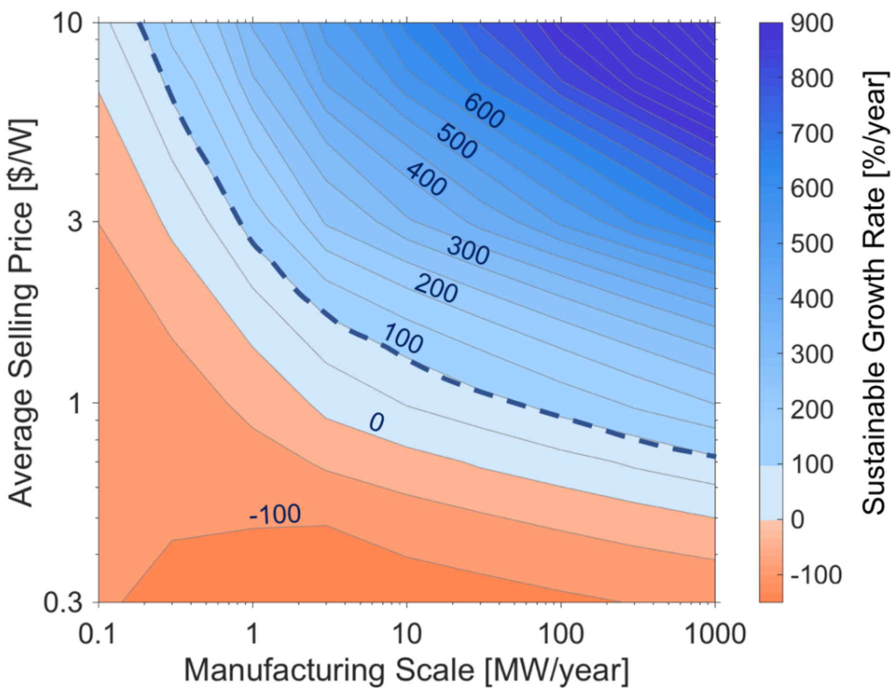

Figure 4: The annual growth rate of a perovskite photovoltaic manufacturing plant versus manufacturing scale and average selling price – the dashed blue line divides the regions above and below 100% year-on-year growth.

Capital-intense investment – solar power market

Combining our bottom-up cost model versus manufacturing scale, and sustainable growth calculator, allows us to compare the different funding options for a perovskite photovoltaics manufacturing startup. As a first step, we analyze the level of equity investment required to build a company that sustainably sells mass market solar modules at \$0.4/W. Firstly, as we have shown that our particular module structure has an MSP of \$0.53/W when manufactured at 1 GW/year, we also model a second case where; given the impact higher cost items such as the ITO-PET film and barrier foils have on the final module cost, we assume that new technologies will be sought to enable the cost of materials to reduce to 80% and 70% of their current costs— a requirement for the cost of roll-to-roll manufacturing of perovskite solar modules to be less than \$0.4/W at all scales we investigate. With these additional cases for variable costs, we calculate the level of capital investment to establish a manufacturing facility versus its profitability or operating margin, as outlined in Fig. 5 (a) (note we exclude the initial startup R&D expenses used to develop the technology in the lab). Given current material costs, our results show that operating margins much less than 0% can be expected for a manufacturing facility with a capacity of 100 MW/year up to 1 GW/year. Considering cases where variable costs are lower, the operating margin of a 1 GW/year factory with variable material costs of 80% of current values is ~1%, and requires an up-front capital investment of \$165 million. If variable costs reduce to 70% of current values, the minimum scale required to operate with a positive operating margin is 202 MW/year, setting the minimum investment in capital items (tools, equipment, facilities and buildings) to create a roll-to-roll perovskite manufacturing company that sells into the mass solar market of \$40 million. This is a reasonable value for an existing large photovoltaics manufacturing company to raise and add a perovskite manufacturing line to their existing capacity, although consideration must be given to "bankability", *i.e.*, the high risk of an unproven technology, especially one that faces a technology risk (stability) and a regulatory risk (lead content), could either dissuade investors or mandate a very large cost of capital. Given the additional costs a new entrant would also incur outside of the capital expense itself, this is a large sum to raise to establish a new company and manufacturing line, and entrepreneurs are likely better off starting a perovskite manufacturing company that targets alternative markets for the first years of operation.

Capitally lighter investment – alternative PV markets

In this section, we investigate what manufacturing scale is required to be profitable in year 1 if average selling prices higher than those available in the mass solar power market can be obtained. Figs. 5 (b) & (c) shows the minimum scale of factory, and investment required, for a company to be profitable versus ASP – showing the scale that leads to an operating margin of 0% considering current material costs and the lower variable cost cases. For the current material costs, the minimum production capacity for profitability versus ASP ranges from 2.1 MW/year for an ASP of \$1/W to >10 GW/year for an ASP of \$0.4/W — the initial capital investment to establish manufacturing facilities ranges from \$1.1 million to over \$1 billion respectively. These figures highlight why thin-film solar companies have struggled to establish themselves when set up to focus exclusively on selling into the mass solar power market, outlining the large sums required to establish a profitable PV manufacturing facility despite the use, in our case, of a low capex technology.

We also consider the cases where variable costs are reduced to 80% and 70% of their current values. Both cases require investments just over \$1 million to enable profitability for selling prices over \$0.7/W, while at the lowest \$0.4/W price considered, there is a dramatic order-of-magnitude reduction in the initial investment required of \$140 million and \$40 million, respectively. It is clear that small increases in material costs can significantly increase the product profitability, enabling much smaller sales volumes to cover the capex depreciation cost each year. The analysis outlines the holistic approach required to co-optimize the scientific, engineering, and economic parameters of a technology for successful commercialization.

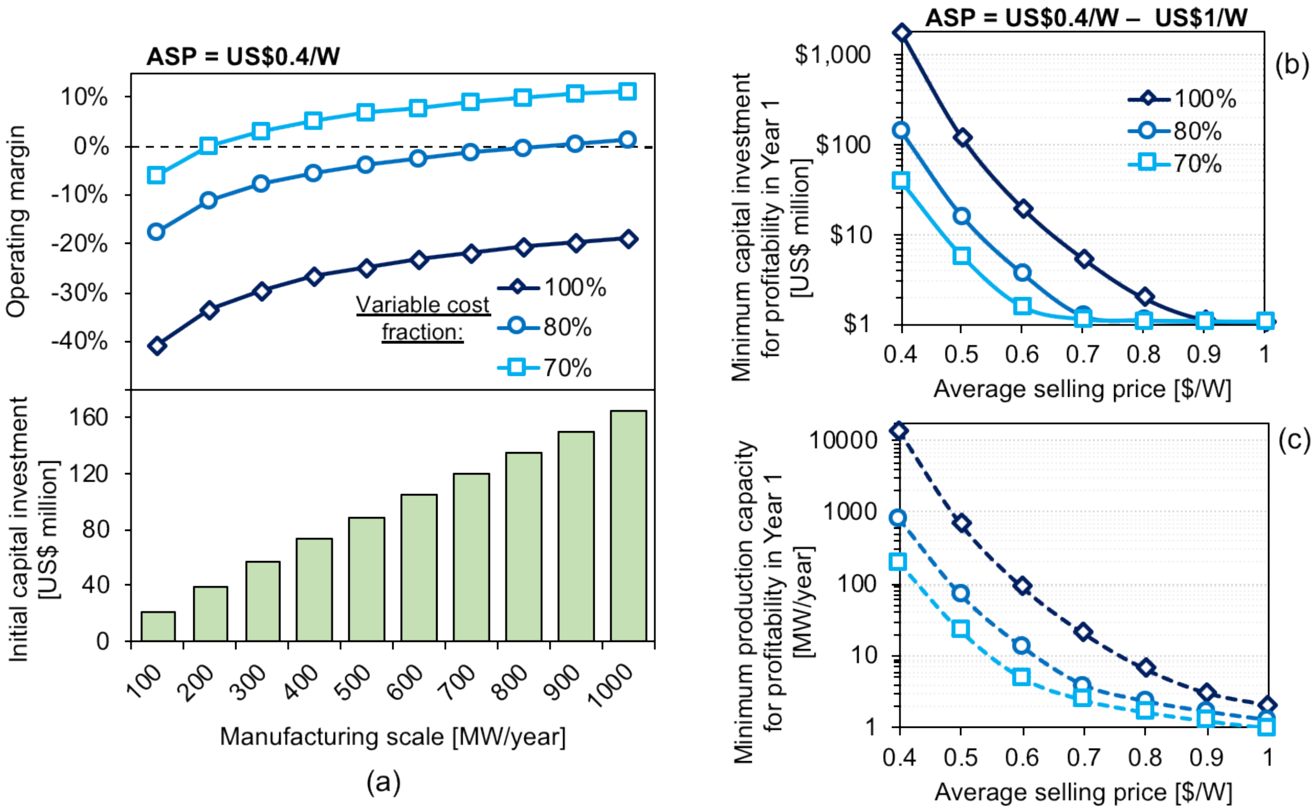

Figure 5: (a) The operating margin versus initial capital investment for a roll-to-roll perovskite manufacturing facility and an average selling price of $0.4/W, and the break-even point in terms of (b) initial capital investment and (c) of production capacity required to establish a profitable roll-to-roll perovskite manufacturing facility over a range of higher selling prices representative of higher-margin niche markets.

V. Conclusions

We presented a technoeconomic model that describes the cost of manufacturing versus scale for a new perovskite PV manufacturing company. A cost model for a roll-to-roll perovskite photovoltaic manufacturing facility versus scale was presented and used to establish a cost range of $3.3/W to $0.53/W for flexible modules manufactured in factory sizes ranging from 0.3 MW/year to 1 GW/year for a baseline scenario. We used these numbers to show the economically sustainable annual growth rates for a company selling photovoltaic modules in different markets, obtaining a wide range of possible values, depending on selling price and scale of manufacturing. Selling into the mainstream utility market requires a prohibitively large upfront investment for a technology with reliability and regulatory (Pb toxicity) risks; we determined minimum levels of investment over $1 billion to establish a profitable manufacturing facility selling into the mass solar power market with an average selling price of $0.4/W. This large initial investment and barrier to market entry for perovskites can be reduced in two ways: (i) the initial investment reduces to $40 million for a 1 GW/year scale, if lower-cost materials, specifically barrier foils and TCO-coated plastics, can be found, highlighting the role of disruptive innovations in related industries, or (ii) selling into niche markets for $1/W or greater, representative of IoT, BIPV, and vehicle-integrated markets, reduces the initial capital investment required to ~$1 million. Our analysis highlights the need to co-optimize the scientific, engineering, and economic parameters of a technology to significantly improve the likelihood of its mass market adoption. Despite the promise of low capex roll-to-roll printing of photovoltaics, the cost of materials could inhibit sustainable scale-up. While we focus on one particular photovoltaic technology, the conclusions of this study extend to other materials systems with similar low-capex cost structures.

Overall, we presented a technoeconomic methodology that can be used to accelerate the commercialization and scale-up of perovskite photovoltaics, finding that the achievable growth rates are compatible with venture capital funding given certain conditions. Our model focuses on just one variant of one cleantech product, flexible perovskite PV modules. Nevertheless, we show how technoeconomic modeling of cleantech products versus scale can be an important tool in assisting a more rapid uptake of new energy technologies that often struggle to leave the lab. We encourage other technologists to adjust their technoeconomic models to consider scale and search for viable and sustainable market on-ramps for their technologies. Technoeconomic modeling has proven to be a useful tool for assessing cleantech industries as they are and the long-term potential of new technologies once they reach scale. Perhaps their greatest capability can be to help technologies cross the “valley-of-death”, and navigate the path from invention to impact.

VI. Methods

Our bottom-up cost modelling approach combines our previous work [15], [19] with perovskite cost models from other authors [22]. Our primary contribution to this field is to adapt these existing models to assess manufacturing costs for low-volume production. For this we assume our perovskite solar panels will be manufactured by roll-to-roll printing on plastic films as in [22] with a PCE of 18%.

a. Materials costs versus scale

The cell architecture we use is sequence D in [22] and includes ITO-coated PET, a printed ZnO nanoparticle electron contact, two-step deposition of FAI + PbI_2 ink and MAI ink, a printed "dry PEDOT:PSS" hole contact and a final encapsulation barrier. We established material costs through multiple sources including Sigma Aldrich, Alibaba, and individual suppliers. Table 1 and Fig. 6 show the costs of materials used in our model, with order-of-magnitude price increases observed for many materials (*e.g.*, MAI, IPA, and Ag paste) when reducing annual production volumes from 1 GW/year to 1 MW/year. We assume the factory owner purchases all materials required for 3 months manufacturing and stores the materials on-site. The maximum costs and % price decline with volume are given in Table 1 with the full range for each material plotted in Fig. 6.

Table 1: Price and economies of scale for the materials used in our photovoltaic module manufacturing model.

Materials	**Unit**	**Usage (Unit/m²)**	**Maximum quote obtained by volume (Unit)**	**Price per unit at maximum volume ($/unit)**	**Minimum quote obtained by volume (Unit)**	**Price per unit at minimum volume ($/unit)**	**% Price decrease per 10x volume increase**	**Source**
ITO coated PET	m^2	1	10,000	$20	100	$31	24.5 %	[30]
ITO Patterning materials	m^2	1	13,000	$8.2	120	$10	10%	[22], [31]
ZnO Nanoparticles	g	0.055	1000	$0.175	25	$1.56	74.48%	[32]
FAI	g	0.14	5000	$1.338	5	$8.41	84.55%	[33]
PEDOT:PSS	mL	4.6	20,000	$0.228	250	$0.65	73.61%	[34]
IPA	mL	11	200,000	$0.003	1000	$0.06	72.68%	[34]
PbI_2	g	0.95	1,300,000	$0.25	50	$1.08	21.8%	[22]
DMF	g	2.9	18,000	$0.047	100	$0.565	202.63%	[34]
MAI	g	0.14	1000	$0.85	5	$3.38	82.64%	[33]
Paste	g	6	200,000	$0.66	5000	$0.79	11.82%	Manufacturer communication
Barrier foils	m^2	2	5,000,000	$10	5000	$20	25.99%	Manufacturer communication
Double sided tape	g	3	1000	$0.75	70	$1.83	116.28%	[35]
Costs assumed to not vary with scale:								
Contact Buttons	pair	13.1	N/A	$0.1	N/A	$0.1	N/A	[22]
Screens	use	13	N/A	$0.01	N/A	$0.01	N/A	[22]
Nitrogen	m^3	8.3	N/A	$0.033	N/A	$0.033	N/A	[22]

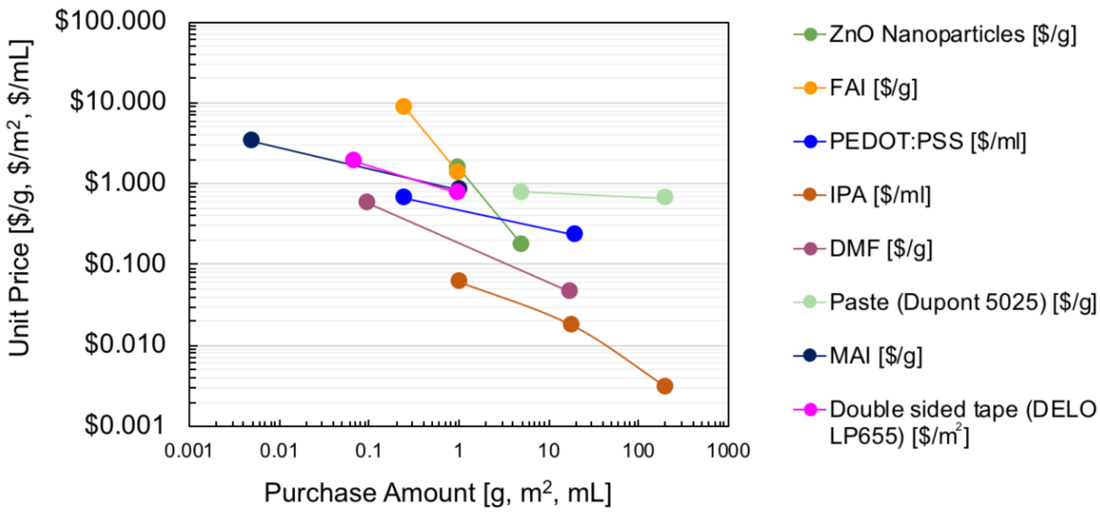

Figure 6: Plot of the maximum and minimum unit prices versus order volume for the materials used in our model.

b. Facility costs

We establish a cost of manufacturing at small scale by assuming some costs (depreciation periods, labor rates…) do not vary with scale. Table 2 summarizes the costs we assume do not vary significantly with scale and we keep constant in our models while Table 3 summarizes the costs we assume do vary with scale.

Table 2: Facility costs for our models that we assume do not vary with scale.

Category	Item	Units	Assumed Value
Location	Factory location		USA
Module Performance	Efficiency		18%
Utilities	Electricity cost	$/kWh	0.07
	Electricity for services	kWh / tool kWh	1
Building related	Building cost	$\$/m^2$	1000
	Floor ratio	total / footprint	3
	Building and facility maintenance rate	% of capex per year	4
Labor	Operator cost	$/h	20
	Indirect labor cost ratio		0.1
	Maintenance technician cost	$/h	25
Depreciation	Facility & equipment	years	7
	Building		25

Table 3: Model assumptions for small-scale and large-scale R&D and SG&A spending.

Cost Assumptions	1 MW/year	1 GW/year
R&D [% of module cost]	20%	5%
Sales General &Admin. [% of module cost]	12%	8%

c. Tools and steps

Krebs *et al*. previously provided numbers for the cost of purchasing the tools required to build an R2R organic PV manufacturing line, including guidance on the price versus scale. The total reported costs were US$678,000 for the ITO patterning tool, slot-die coater, screen printer, laminator, equipment for sheeting and pinning and a module tester — all R2R tools — with a production capacity of 3.6 MW/year [27]. We adjust the cost of the tools for inflation for a new total tool cost of US$797,000 with the individual tools outlined in Table 4.

Table 4: Equipment input cost assumptions for a single production tool.

Equipment	**Tool cost (US$ '000)**	**Facility cost (% of tool cost)**	**Floor space (m^2)**	**Spare parts (% capex/year)**	**Electricity usage (kW)**
ITO Patterning tool	118	30	15	10	15
Slot Die Coater	465	30	12	10	25
Screen printer	79	30	10	10	15
Laminator	33	5	10	4	25
Sheet and Pin	34	2	5	4	10
Module tester	68	3	5	4	2

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